

Task 3 Report – Bridge Construction and Related Activities

Feasibility of Nonproprietary Ultra-High Performance Concrete (UHPC) for Use in Highway Bridges in Montana: Implementation

Prepared By:

Elias Hendricks

Graduate Research Assistant

Michael Berry, PhD

Associate Professor

and

Kirsten Matteson, PhD

Assistant Professor

Civil Engineering Department

College of Engineering

Montana State University – Bozeman

Prepared for the

MONTANA DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

June, 2022

Disclaimer Statement:

This document is disseminated under the sponsorship of the Montana Department of Transportation (MDT) and the United States Department of Transportation (USDOT) in the interest of information exchange. The State of Montana and the United States assume no liability for the use or misuse of its contents.

The contents of this document reflect the views of the authors, who are solely responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the views or official policies of MDT or the USDOT.

The State of Montana and the United States do not endorse products of manufacturers.

This document does not constitute a standard, specification, policy or regulation.

Alternative Format Statement:

Alternative accessible formats of this document will be provided on request. Persons who need an alternative format should contact the Office of Civil Rights, Department of Transportation, 2701 Prospect Avenue, PO Box 201001, Helena, MT 59620. Telephone [406-444-5416](tel:406-444-5416) or Montana Relay Service at 711.

Acknowledgements:

The authors would like to acknowledge the financial support for this project provided by the Montana Department of Transportation (MDT). The authors would also like to recognize and thank the MDT Research Section and the technical panel for their participation in this project.

Table of Contents

1	Introduction	1
2	Background.....	1
3	Scope of Report	1
4	Trail Creek Structures Overview and MT-UHPC Special Provisions	2
4.1	Bridge Overview.....	2
4.2	MT-UHPC Batching and Mixing Procedures	4
4.3	MT-UHPC Special Provisions.....	8
4.4	Quality Control Testing Procedures	9
5	Trial Pour and Bridge Joint Mockups	9
5.1	Overview	9
5.2	UHPC Batching, Mixing, and Results.....	11
5.3	Joint Mockups.....	12
5.4	Discussion of Results.....	16
6	Bridge Construction.....	16
6.1	Demolition and Site Preparation.....	16
6.2	Pile Caps	18
6.3	Longitudinal Beam/Deck Elements.....	23
6.4	Keyway Grinding	29
6.5	Timeline of UHPC Related Activities	33
6.6	Summary of UHPC Strengths.....	34
6.7	Costs	35
7	Summary and Key Findings	35
8	References	36

List of Figures

Figure 1: General location of Trail Creek bridges	2
Figure 2: Specific location of Trail Creek bridges.....	3
Figure 3: Trail Creek bridges prior to replacement.....	3
Figure 4: Structural plans for Trail Creek bridges	4
Figure 5: Sacks of MT-UHPC in storage container.....	6
Figure 6: Sacks of MT-UHPC dry material on the jobsite	6
Figure 7: Sack of dry mix being added to the mixer.....	7
Figure 8: Water, HRWR, and steel fibers being weighed on site	7

Figure 9: Steel fibers being added to the mixer	8
Figure 10: Mockup pile-to-pile cap connection	10
Figure 11: Mockup keyway connections	10
Figure 12: Dry mix being added to mixer	11
Figure 13: Water and HRWR being added to mixer	12
Figure 14: Flow test of MT-UHPC during mockup	12
Figure 15: Keyway mockup	13
Figure 16: MT-UHPC being placed into keyway mockup	13
Figure 17: Flat keyway mockup after MT-UHPC placement	14
Figure 18: Sloped keyway mockup after MT-UHPC placement	14
Figure 19: UHPC being ground around keyway	15
Figure 20: Ground UHPC surface after a 6-hr cure time	15
Figure 21: UHPC being added to pile cap connection mockup	16
Figure 22: Bridge site after removal of existing bridge	17
Figure 23: Demolished bridge after removal	17
Figure 24: Reclaimed rebar from demolished bridge	18
Figure 25: Uncovered pile caps and prepared surface prior to cap placement	19
Figure 26: Pile cap being placed on steel pipe piles	19
Figure 27: Pile cap void to be filled with UHPC with thermocoupling wires installed	20
Figure 28: MT-UHPC being placed into pile cap sockets	20
Figure 29: MT-UHPC placement on pile cap	21
Figure 30: MT-UHPC dry mix being added to mixer on pile cap	21
Figure 31: Ice formed in the bottom of the mixer prior to the start of construction	22
Figure 32: Pile cap after UHPC placement, just prior to the beam placement	22
Figure 33: First longitudinal beam element being placed	23
Figure 34: Second beam element being placed on pile caps	23
Figure 35: First two beam elements after placement, with visible keyway	24
Figure 36: Final longitudinal beam element being placed	24
Figure 37: Longitudinal beam elements being leveled	25
Figure 38: Stainless steel shear tabs just prior to welding	25
Figure 39: Wood slats glued to the top surface of beams around keyways	26
Figure 40: MT-UHPC being placed into keyways	27
Figure 41: UHPC being placed into beam dowel hole, connecting it to pile cap	27
Figure 42: Keyways with top forming	28
Figure 43: Complete bridge with keyways after UHPC placement and top forming	28

Figure 44: Keyways after removal of wood slats, just prior to grinding	29
Figure 45: Bridge during grinding process	29
Figure 46: Bridge deck immediately after keyway grinding	30
Figure 47: Keyways after grinding	31
Figure 48: Finished keyway after epoxy application	31
Figure 49: Bridge deck after epoxy application on all keyways	32
Figure 50: First vehicle to cross bridge after keyways reach required strength	32
Figure 51: Timeline of UHPC related activities on the first bridge	33
Figure 52: Timeline of UHPC related activities on the second bridge	33

List of Tables

Table 1: Mix Proportions for 1 yd ³	5
Table 2: Summary of mockup mix results	11
Table 3: Compressive strength and flow results from first bridge	34
Table 4: Compressive strength and flow results for second bridge	34
Table 5: Cost of MT-UHPC per cubic yard	35

1 Introduction

Ultra-high performance concrete (UHPC) has mechanical and durability properties that far exceed those of conventional concrete. However, using UHPC in conventional concrete applications has been cost prohibitive, with commercially available/proprietary mixes costing approximately 30 times more than conventional concrete. Previous research conducted at Montana State University (MSU) has focused on the development and evaluation of nonproprietary UHPC mixes made with materials readily available in Montana. These mixes are significantly less expensive than commercially available UHPC mixes, thus opening the door for their use in construction projects in the state. The focus of the proposed project is on taking this material beyond the laboratory, and successfully using it on a bridge project in Montana, specifically for field cast joints. This project is a required step to fully understand and capitalize on the benefits of using UHPC for this application and increase the performance, durability, and efficiency of Montana bridges.

The specific tasks associated with this research are as follows:

Task 0 – Project Management

Task 1 – Literature Review

Task 2 – Close Minor Research Gaps

Task 3 – Bridge Construction and Related Activities

Task 4 – Monitoring Bridge Performance

Task 5 – Analysis of Results and Reporting

This report documents the work completed as part of Task 3 – Bridge Construction and Related Activities.

2 Background

Previous research at MSU developed a nonproprietary mix design that has a 28-day compressive strength of 18 ksi, and is significantly less expensive than proprietary UHPC mixes [1, 2]. The focus of this project is on the field implementation of the MT-UHPC developed in this initial research. Specifically, the use of MT-UHPC on two bridges on Highway 43 near Lost-Trail Pass outside of Wisdom, MT. The MT-UHPC was used to connect precast pile caps to steel piles, and was used in longitudinal joints between precast/prestressed hollow-core bridge beams.

3 Scope of Report

This task report documents the construction process and lessons learned in the field implementation of MT-UHPC on the Trail Creek bridges. Specifically, this report: (1) briefly documents the state of the existing bridges prior to replacement, (2) provides details about the replacement bridges and where MT-UHPC will be used, (3) details the on-site mixing and batching procedures for the MT-UHPC, (4) documents the trial pours and connection mockups, (5) discusses the construction process, schedule, and (6) summarizes key findings from this research.

4 Trail Creek Structures Overview and MT-UHPC Special Provisions

This chapter provides details on the location and state of the Trail Creek structures to be replaced with precast elements using MT-UHPC field-cast joints. It also documents the general procedures used in these bridges to batch, store, and field-mix the MT-UHPC. This chapter concludes with a discussion of the Special Provisions used to prescribe the field implementation of MT-UHPC on the Trail Creek bridges, and the quality control strategies used during construction.

4.1 Bridge Overview

The two Trail Creek bridges selected for replacement are located in Southwest Montana on Highway 43, about 17 miles west of Wisdom, MT near the May Creek Campground, as shown in Figure 1 and Figure 2. The bridges were significantly deteriorated, and in need of replacement. One of the bridges is shown in Figure 3, which highlights the deteriorated state of the bridges prior to replacement.

From Wisdom, there are no convenient detours around this location, and therefore Highway 43 must be shut down to through-traffic during construction of each bridge. The average daily cost to the traveling public resulting from this road closure was estimated to be \$2,500 per hour, and thus an accelerated bridge construction (ABC) procedure was chosen for the bridge replacements with a specified 96-hour construction window for each bridge. Specifically, the chosen procedure consisted of precast elements assembled on-site with MT-UHPC used for all field-cast joints. A monetary incentive/disincentive was applied to the contract to incentivize the timely construction of the bridges.

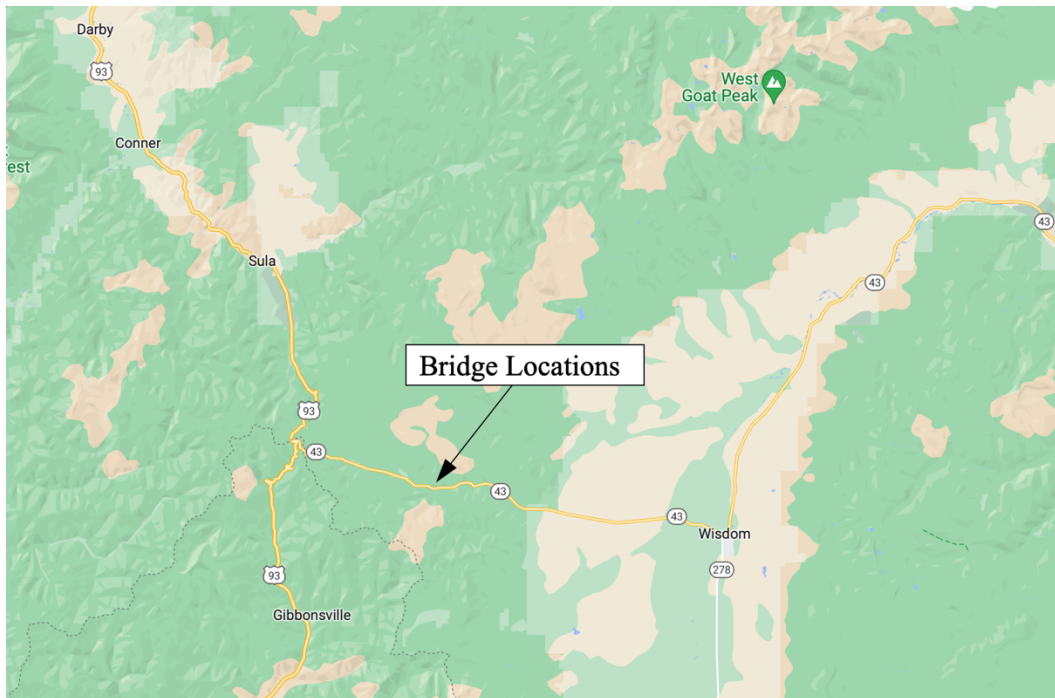


Figure 1: General location of Trail Creek bridges

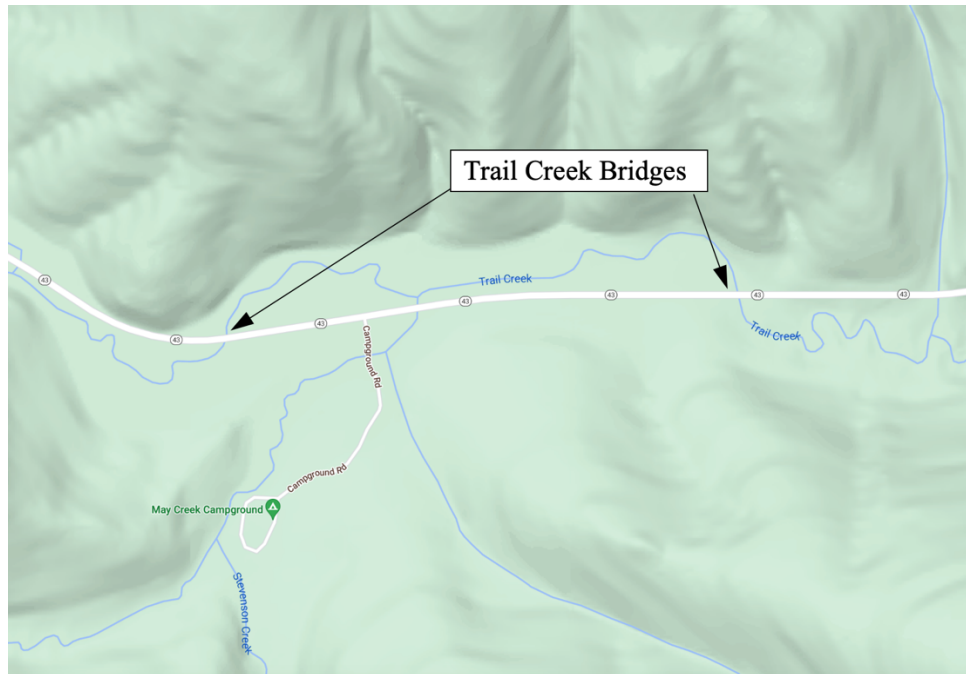


Figure 2: Specific location of Trail Creek bridges



Figure 3: Trail Creek bridges prior to replacement

Each replacement bridge had a single span of approximately 60 ft, and was constructed with precast elements connected with MT-UHPC. An overview of the plans is provided in Figure 4. The support structure for each bridge consisted of two precast pile caps, each cast with three 24-in diameter connection sockets (constructed with embedded corrugated metal pipes) at the locations of the piles. The main span and riding surface of the bridge consisted of eight precast/prestressed hollow-core beams placed directly

on top of the pile caps adjacent to each other. These beams each had small sockets on either end to be placed on top of embedded dowels on the pile caps. The bridges also included four precast wingwalls to be connected to the pile caps via embedded dowels on the caps. MT-UHPC was used for all field-cast connections, including the pile to pile-cap connections, the connections between the beams and caps, the wing walls, and the longitudinal shear-keys between adjacent beams, as shown in Figure 4.

The following sections provides details on the batching, storage, and mixing of the MT-UHPC.

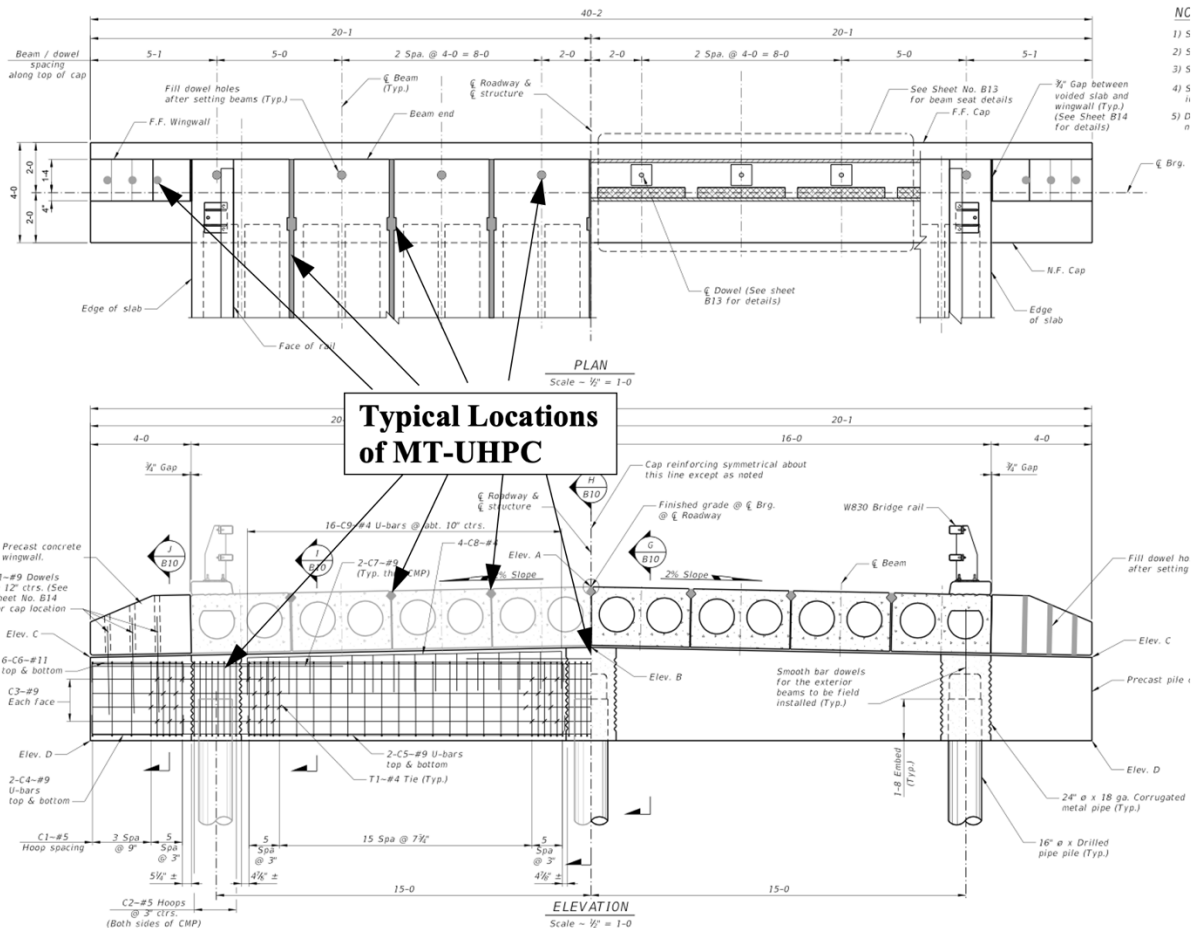


Figure 4: Structural plans for Trail Creek bridges

4.2 MT-UHPC Batching and Mixing Procedures

The mix proportions used in the MT-UHPC are provided in Table 1. It should be noted that these mix proportions reflect a 2.5% increase in the water and HRWR relative to the mix proportions used in previous research. The water and HRWR were increased during bridge construction to help the UHPC turn over, and improve its workability. More details on the specific materials used in this project will be provided in the final report; however, a brief summary of materials is included here. The cement was a Type I/II/IV from

the GCC cement plant in Trident, MT. The fly ash was a Class F ash sourced from Prairie State Energy Campus in Marissa, IL. The fine aggregate was a masonry sand processed and packaged by QUIKRETE near Billings, MT. It should be noted that the fly ash, cement, and sand were all purchased from QUIKRETE and delivered in 1-yd³ sling bags. The silica fume was MasterLife SF 100 from BASF. The high range water reducer (HRWR) was CHRYSO Fluid Premia 150, which is a polycarboxylate ether (PCE)-based product. The steel fibers were sourced by Hiper Fiber and were 13 mm long, had a diameter of 0.2 mm and a tensile strength of 285 ksi.

Table 1: Mix Proportions for 1 yd³

Item	Weight (lbs)
Water	306.2
Portland Cement	1299.5
Fly Ash	371.3
Silica Fume	278.4
HRWR	66.0
Steel Fibers	262.9
Fine Aggregate	1556.4

It was estimated that each structure would require approximately 5 yd³ of MT-UHPC for the field cast joints. After acquiring enough materials to cast a total of 10 yd³ of UHPC, and several months prior to the bridge construction, the dry ingredients were batched and premixed to save time on the jobsite. The constituent dry materials (i.e., cement, fly ash, silica fume, and sand) were weighed out in proportion to 3-ft³ batches then premixed and bagged in sling bags. The premixing was done in accordance to the methods recommended in previous MSU research, using the IMER Mortarman 360 mixers that were used for mixing the MT-UHPC. Once mixed, the 3-ft³ sacks of MT-UHPC were stored in a shipping container shown in Figure 5. This shipping container contained approximately 100 sacks of MT-UHPC, and provided a convenient method of protecting the material from the elements and transporting it to the jobsite. On the jobsite, these sacks were removed from the storage container and transported to the mixing location on a flatbed, as seen in Figure 6.

During construction, two IMER Mortarman 360s were used to mix the MT-UHPC. First the premixed dry ingredients were added to the mixer by hoisting the sack and depositing it in the mixer through the hole in the bottom, as shown in Figure 7. The HRWR and mix water were weighed on site (Figure 8), and then added to the mixer. The dry premix, water, and HRWR were then mixed until the MT-UHPC turned over (approximately 5-10 minutes) and became fluid. Once turned over, the steel fibers were added (Figure 9), and the MT-UHPC was mixed in for approximately 5 additional minutes to evenly distribute the fibers. After this mixing was complete, the MT-UHPC was removed from the mixer and placed in the field cast joints. Details on the placement of the field-cast joints are discussed in the following chapters.



Figure 5: Sacks of MT-UHPC in storage container



Figure 6: Sacks of MT-UHPC dry material on the jobsite



Figure 7: Sack of dry mix being added to the mixer



Figure 8: Water, HRWR, and steel fibers being weighed on site



Figure 9: Steel fibers being added to the mixer

4.3 MT-UHPC Special Provisions

As part of this research, in coordination with MDT, Special Provisions were created to prescribe the procedures and requirements of the MT-UHPC. These Special Provisions outline all key aspects of the MT-UHPC and will be included in the appendix of the final report. Some key takeaways from these provisions are itemized below.

- The constituent materials and mixing methods recommended by previous MSU research must be used.
- The minimum compressive strength of the MT-UHPC prior to backfilling around pile caps, operating compaction equipment near the structures, or placing beams on the pile caps is 4,000 psi.
- The minimum required 28-day compressive strength of the MT-UHPC is 12,000-psi.
- The state will supply two IMER Mortarman 360 mixers.
- The MT-UHPC may not be placed at air temperatures below 40°F nor above 80°F.
- The cure time of the MT- UHPC must be established to meet the project schedule and compressive strength requirements defined in the specification.
- A trial pour and joint mockups must be completed. This exercise will simulate conditions for mixing, placing, curing, and surface finishing the MT-UHPC for the pile-to-pile cap connection and the longitudinal deck joint.
- The grinding procedures are prescribed, which require a minimum compressive strength of 3 ksi prior to grinding.
- The quality control testing procedures are prescribed.
- The basis for payment is established.

It should be noted that although these provisions outline the required quality control testing procedures, these procedures were modified prior to the construction project, and are discussed in the following section.

4.4 Quality Control Testing Procedures

The quality control procedures outlined in the Special Provision were modified in an effort to reduce the amount of MT-UHPC required for testing during construction, and to provide a more efficient means of monitoring early strength gain. Specifically, the requirements used for strength testing were as follows.

- Five 3x6 inch cylinders from 3 batches of MT-UHPC were obtained from each application of the material, equating to 15 total cylinders per placement.
- The sets of 5 cylinders were pulled from batches of MT-UHPC near the beginning, middle, and end of each placement.
- From the sets of 5 cylinders, 2 were cured on site in a cure box (provided by MDT), transferred to MSU at the end of construction, cut and ground by MSU, placed in MSU's cure room, and then transferred to MDT for 28-day acceptance testing.
- The remaining 3 cylinders from each batch were field cured next to the bridge for 24-48 hours, and transferred, prepped, cured, and tested by MSU.

The maturity method was used to predict the early compressive strength of the concrete, and subsequently determine when the joints reached the minimum strength of 4 ksi required for backfilling around pile caps, operating compaction equipment near the structures, placing beams on the pile caps, and opening the bridges to traffic. The maturity curves discussed in Task Report 2 (developed using these exact materials) were used for this method. Using these maturity curves, it was determined that this 4 ksi minimum strength threshold would be expected to occur at a Temperature Time Factor (TTF) of around 375°C-hrs. The TTF was monitored on site using maturity meters with embedded thermocouples in all pile cap and keyway joints.

5 Trial Pour and Bridge Joint Mockups

5.1 Overview

Prior to placement of the MT-UHPC in the actual bridges, a trial pour was conducted near the location of the bridges where MT-UHPC was placed in mockup field-cast joints. During this trial, MT-UHPC was mixed on site using the same methods and under the same environmental conditions expected on the day of construction. After mixing, the MT-UHPC was placed into three replica field-cast joints. Specifically, the MT-UHPC was placed into a mockup pile-to-pile cap connection (Figure 10) and two keyways (Figure 11).



Figure 10: Mockup pile-to-pile cap connection



Figure 11: Mockup keyway connections

5.2 UHPC Batching, Mixing, and Results

The mockup trial pours took place on June 3, 2021 at the contractor's yard in Wisdom, MT, where the temperatures were around 65°F at the time of the first mix (around 9 am), and climbed to 88°F throughout the day. Figure 12 shows the MT-UHPC dry mix being added to the mixer during the first batch, and Figure 13 shows the water and HRWR being added. Two mixes were conducted during the trial. Both mixes performed well, with spreads of around 10 inches (Figure 14) and 28-day compressive strengths of 15.1 and 17.1 ksi, for first and second mix, respectively. A summary of results from these mixes is provided in Table 2.

Table 2: Summary of mockup mix results

Mix	Application	Spread (in)	24-hr strength (ksi)	48-hr strength (ksi)	7-day strength (ksi)	28-day strength (ksi)
1	Keyway	10	9.4	9.2	11.5	15.1
2	Pile Cap	10	10.3	10.7	13.4	17.1



Figure 12: Dry mix being added to mixer



Figure 13: Water and HRWR being added to mixer



Figure 14: Flow test of MT-UHPC during mockup

5.3 Joint Mockups

As mentioned above, the MT-UHPC was placed into two keyway mockups, shown in Figure 11. One of these keyways was sloped to simulate the expected conditions of the actual bridges. As is common with most UHPC, air within the mix gets entrapped near the top surface during initial set. Therefore, the MT-UHPC was cast $\frac{1}{2}$ inch above the surface of the deck to facilitate grinding of this top surface. This overcasting of UHPC was implemented using $\frac{1}{2}$ -inch thick wood strips glued to the top surface of the deck around the keyways, as shown in Figure 15. Also, foam sealant was used at the bottom of the keyway to ensure that the MT-UHPC did not flow out the bottom of the connection, shown in Figure 15b.

After mixing, the MT-UHPC was placed into the keyways using buckets, as shown in Figure 16. This method worked well for these mockups, and the UHPC easily flowed into the joints with no need for vibration. However, the sloped specimen highlighted the need for top-forming of the connection. In this

specimen, as expected, the MT-UHPC overflowed the formwork on the low end of the specimen and did not completely fill the joint on the high end. Both the flat and sloped specimens after placement of the MT-UHPC are shown in figures 17 and 18, respectively. It should be noted that thermocouples were embedded in the keyway to estimate early strength gain and assist in determining the proper time for grinding.



a) full specimen



b) inside keyway showing foam sealant

Figure 15: Keyway mockup



Figure 16: MT-UHPC being placed into keyway mockup



Figure 17: Flat keyway mockup after MT-UHPC placement



Figure 18: Sloped keyway mockup after MT-UHPC placement

After placement and initial curing, the surface of the UHPC needed to be ground down to the top surface of the deck elements. The initial grinding occurred over a portion of one of the mockups after approximately 6 hours with a TTF of 173°C-hrs, which corresponded to a compressive strength of less than 1 ksi. This grinding was carried out using a handheld angle grinder with concrete grinding wheel. While the top surface was easily ground at this low strength, it was determined that this was too early since the steel fibers were being pulled from the UHPC during the process. More grinding occurred the following morning at approximately 20 hours, with better results. However, the maturity meter had been removed from the specimens prior to this grinding, and therefore the estimated strength of the UHPC was unknown during this grinding. It should be noted that the Special Provisions specify that the MT-UHPC reach 3 ksi before grinding. Figure 19 shows a specimen being ground, while Figure 20 shows a specimen after grinding at 6 hours.



Figure 19: UHPC being ground around keyway



Figure 20: Ground UHPC surface after a 6-hr cure time

In regards to the pile cap connection mockup, the UHPC was simply added to the connection with buckets, as shown in Figure 21. There were no issues with this process, and this connection required no grinding of the top surface since this concrete will be covered by the longitudinal beam elements in the actual bridge project.



Figure 21: UHPC being added to pile cap connection mockup

5.4 Discussion of Results

Some key takeaways from the trial pours and joint mockups are as follows:

- MT-UHPC was successfully batched and mixed in the field using the exact materials, mixers and methods to be used in the actual bridge project. The flows of the trial mixes were around 10 inches, and the compressive strengths exceeded the minimum specified 28-day strength of 12 ksi, with an average strength of 16.1 ksi.
- The methods used to form and place the UHPC in the connection mockups were primarily successful. However, the UHPC in the sloped-keyway mockup demonstrated the need for top forming the keyways, as the UHPC in these connections overflowed at the low end and fell short on the high end.
- Grinding the UHPC before it reaches a strength of 1 ksi resulted in a rough surface on the UHPC and steel fibers being pulled from the material. It is recommended that the MT-UHPC reach at least 3 ksi prior to grinding, as is specified in the Special Provisions.

6 Bridge Construction

This chapter discusses the construction process used for the Trail Creek bridges. It should be noted that both bridges followed the same process described below and had identical structural systems.

6.1 Demolition and Site Preparation

As stated previously, each bridge had a 96-hour shutdown window for construction. The shutdown period began with applying containment methods to prevent the pollution of Trail Creek, and the demolition of the existing bridge. The bridge site after demolition is shown in Figure 22, which also shows the timber

piles from the old bridge and the containment methods in place. The old bridge after removal is shown in Figure 23. It should be noted that the rebar was removed from the old bridge and recycled (Figure 24).



Figure 22: Bridge site after removal of existing bridge



Figure 23: Demolished bridge after removal



Figure 24: Reclaimed rebar from demolished bridge

6.2 Pile Caps

For each bridge, 6 drilled steel pipe piles (3 on each side of the span) were placed and covered prior to the beginning of the shutdown window. After the banks of the river were prepared for erosion control, these drilled piles were uncovered, and the soil around the piles was prepared for the placement of the pile caps. This soil preparation included achieving proper compaction and elevations. The uncovered piles are shown in Figure 25, along with one of the precast pile caps being moved into position for placement. As can be observed in this figure, an expanding foam sealant was placed on the ground at the locations of the sockets to prevent the UHPC from potentially flowing out of the base when being filled.

Once the surface was prepared, the pile caps were then placed on top of the piles, bearing on the compacted soil. Figure 26 shows a pile cap being placed. Thermocouples were then placed within the sockets to monitor the maturity and subsequent strength of the MT-UHPC. MT-UHPC was then used to complete the connection between the piles and the pile caps. Figures 28-30 show MT-UHPC being directly added into the connections. Figure 32 shows the pile cap after the placement of the MT-UHPC, just before the placement of the beam elements.

It should be noted that UHPC placement commenced for both bridges early in the morning when outside temperatures were around 25°F. With the exception of the first mix on the first bridge, there were no issues mixing and placing the UHPC at this low temperature. On the morning of the first bridge, both mixers had small amounts of ice accumulated in their drums (Figure 31). One of these mixers was warmed up in order to remove this ice, and the other was not. The UHPC in the mixer that had not been warmed up took too long to turn over, and this mix began setting within the mixer. Whereas, the mix that was placed in the warmed-up mixer worked well, with no issues. The remainder of mixes worked well in both mixers.

Therefore, on the second bridge, both mixers were first warmed up by simply adding water to the mixer for several minutes prior to initiating mixing for the day.



Figure 25: Uncovered pile caps and prepared surface prior to cap placement



Figure 26: Pile cap being placed on steel pipe piles



Figure 27: Pile cap void to be filled with UHPC with thermocoupling wires installed

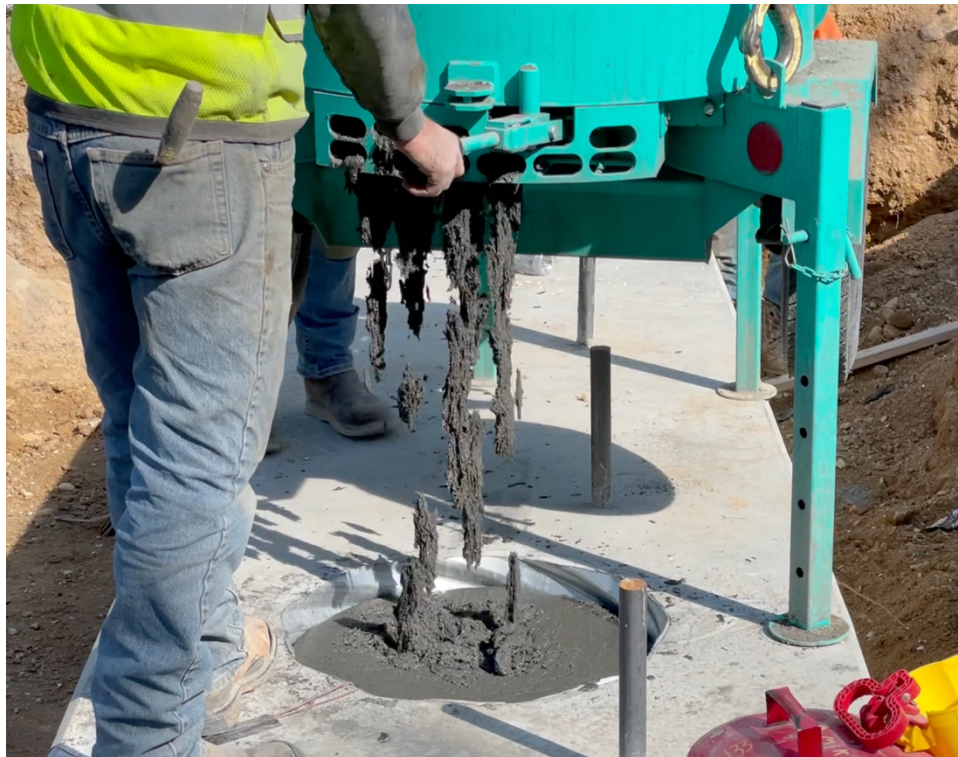


Figure 28: MT-UHPC being placed into pile cap sockets



Figure 29: MT-UHPC placement on pile cap



Figure 30: MT-UHPC dry mix being added to mixer on pile cap



Figure 31: Ice formed in the bottom of the mixer prior to the start of construction



Figure 32: Pile cap after UHPC placement, just prior to the beam placement

6.3 Longitudinal Beam/Deck Elements

After the MT-UHPC was determined to reach the required strength of 4 ksi (via the maturity method), the 8 precast/prestressed hollow-core beam elements were placed on top of the pile cap, aligning the holes in the beams with the embedded dowls on the cap. This process is shown at various stages in figures 33-36.



Figure 33: First longitudinal beam element being placed



Figure 34: Second beam element being placed on pile caps



Figure 35: First two beam elements after placement, with visible keyway



Figure 36: Final longitudinal back element being placed

After the beams were placed, some adjustments (Figure 37) were made to ensure that there were not excessive differences between the tops of adjacent beams. The contractor began these adjustments with the middle beam and then worked towards the edges of the bridge. Once a beam was adjusted, the shear tabs within the keyways were welded. Figure 38 shows these the stainless-steel shear tabs just prior to welding.



Figure 37: Longitudinal beam elements being leveled



Figure 38: Stainless steel shear tabs just prior to welding

Before the placement of MT-UHPC within the keyways, $\frac{1}{2}$ in. wood slats were glued to the surface of the bridge deck around the keyways, as shown in Figure 39. This was done, as is common in all UHPC applications, to allow for over casting of the MT-UHPC. The top surface of UHPC contains a large amount

of entrapped air due to a skin forming on the surface of the concrete, which will be ground down in a later step. MT-UHPC was then placed into these keyways, and top formed to ensure that the UHPC evenly fills the sloped keyways.



Figure 39: Wood slats glued to the top surface of beams around keyways

For the keyway placement, the UHPC was batched at the end of the bridge and then transported to the keyway for placement using a wheelbarrow. At first, the MT-UHPC was placed directly into the keyway as shown in Figure 40a. However, it was determined that using a trough (shown in Figure 40b) was more efficient. Placement of MT-UHPC in the keyways began at the low end of the bridge and ended at the high end. The trough was slowly moved along the length of the keyway at a rate slow enough to allow the UHPC to disperse evenly within the joint. As the material was placed, it was immediately top formed behind the trough. This involved workers standing on the top-forming boards until fasteners were installed to maintain pressure on the material moving forward. It should also be noted that during this step, UHPC was also placed into the wingwall and beam dowel holes, as shown in Figure 41. One of the bridges with completed UHPC and top forming is shown in figures 42 and 43.



a) UHPC directly added to keyway



b) UHPC being added to keyway using trough

Figure 40: MT-UHPC being placed into keyways



Figure 41: UHPC being placed into beam dowel hole, connecting it to pile cap



Figure 42: Keyways with top forming



Figure 43: Complete bridge with keyways after UHPC placement and top forming

6.4 Keyway Grinding

Once the MT-UHPC was determined to have reached an appropriate strength for grinding, the forms were stripped from the top of the keyways and the MT-UHPC was ground to the top surface of the beam elements. The stripped UHPC prior to grinding is shown in Figure 44, the grinding process is shown in Figure 45, and the bridge immediately after grinding is shown in Figure 46.



Figure 44: Keyways after removal of wood slats, just prior to grinding



Figure 45: Bridge during grinding process

At several locations across the bridge, the top surface of the UHPC contained a significant amount of air pockets after grinding, which was most likely due to insufficient depths of UHPC in these locations. Therefore, the decision was made by MDT to epoxy-coat the top surface of the UHPC. The finished keyways before and after the addition of epoxy are shown in Figure 47 and Figure 48, respectively. The bridge with all keyways epoxied is shown in Figure 49.

The strength of the MT-UHPC within the keyways was monitored via the maturity method and embedded thermocouples throughout the keyways. Once the keyways reached the required minimum compressive strength of 4 ksi, the earthwork (e.g., backfilling and compaction) was completed on the approaches, and the bridges were opened to traffic. These approaches were paved at a later time and did not prohibit the opening of the bridge. Figure 50 shows the first vehicle to cross the first bridge after the keyways came to strength.

The following section discusses the timeline for both bridges.



Figure 46: Bridge deck immediately after keyway grinding



a) keyway



b) keyway with air pockets

Figure 47: Keyways after grinding



Figure 48: Finished keyway after epoxy application



Figure 49: Bridge deck after epoxy application on all keyways



Figure 50: First vehicle to cross bridge after keyways reach required strength

6.5 Timeline of UHPC Related Activities

The total project timeline for each bridge spanned approximately 96 hours. The first 24 of which included the demolition of the old bridge and preparation of the site for the pile cap placement. This section specifically documents the UHPC implementation and related tasks, which took place over the course of approximately three days. The timeline for both bridges after demolition and site preparation are presented in Figure 51 and Figure 52. In these figures, the cure time for the MT-UHPC to reach the required 4 ksi compressive strength are highlighted in yellow.

As can be observed in these figures, the placement of MT-UHPC in the pile cap connections took 5-6 hours on both bridges, while placement in the keyways took approximately 3 hours. This difference in time is due to the fact that more material was placed in the pile caps (3 yd³) than were placed in the keyways (2 yd³). In regards to cure time, the pile caps took 11-13 hours to reach the required 4 ksi for construction loads, while the keyways took 20-23 hours to reach this strength. This contrast in cure time between the pile caps and keyways was largely due to variations in temperatures during curing. The pile cap connections were placed in the morning and were exposed to elevated daytime temperatures during curing, with direct sunlight exposure. Whereas, the keyways were placed in the afternoon and cured overnight at significantly lower temperatures (in the 20s °F). Further, the pile cap connections had a larger mass of concrete enclosed in the connection, where heat of hydration elevated the temperatures during curing. The keyways were significantly thinner and more exposed to the open air and lower temperatures. Longer cure times observed for the keyways resulted in a slight delay in the construction schedule. This may be avoided in future applications by possibly using heated blankets if low temperatures are expected.

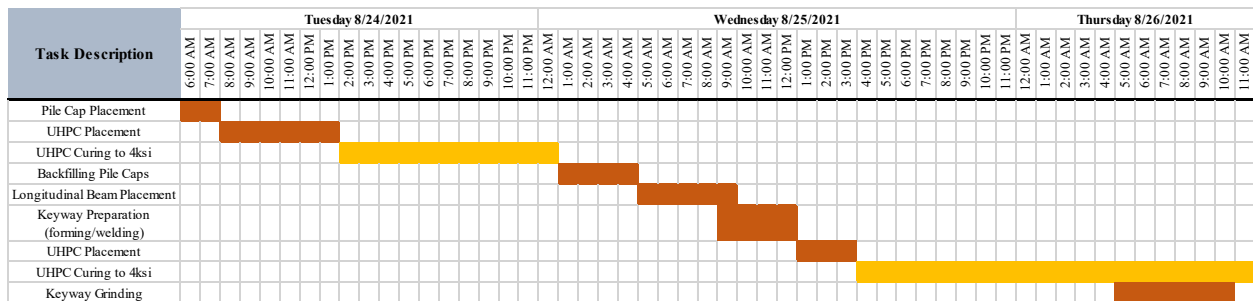


Figure 51: Timeline of UHPC related activities on the first bridge

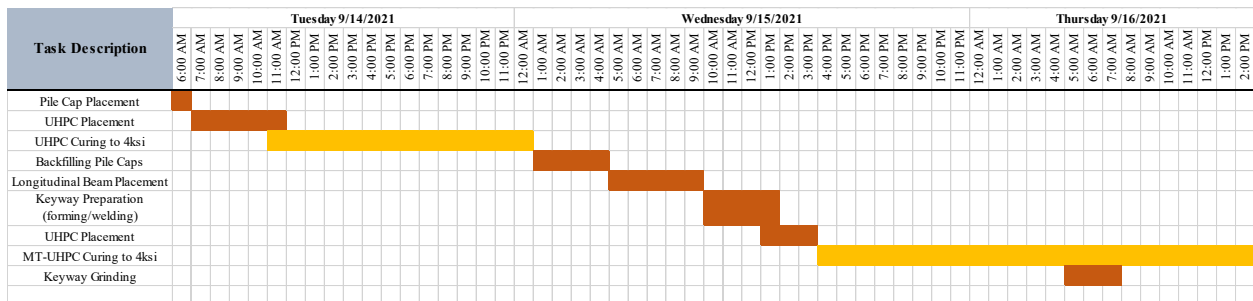


Figure 52: Timeline of UHPC related activities on the second bridge

6.6 Summary of UHPC Strengths

The results from the quality control testing of the MT-UHPC are provided in Table 3 for the first bridge and Table 4 for the second bridge. Included in both tables are the ambient air temperature at the time of sampling, and included in Table 4 are the internal UHPC temperatures at the time of sampling. The compressive strengths reported in these tables are the averages of 2 cylinders that were obtained from mixes near the beginning, middle, and end of each day of UHPC placement. These cylinders were cured in a cure box on site until being transferred to the cure room at MSU. The quality control testing procedures are discussed in Section 4.4.

As can be observed in these tables, all MT-UHPC mixes reached the minimum specified compressive strength of 12 ksi at 28 days, with average strengths of 17.6 ksi and 17.5 ksi for bridge 1 and 2, respectively. All flows were greater than 10 inches on the first bridge, while the flows on the second bridge had several samples with 9.5 in flows and one with 8.75 in. The decreased flows on the second bridge are most likely due to the increased wind observed at the job site during the construction of this bridge. However, all flows were within what was required for placement on the bridge.

As can be observed in both tables, temperature had a significant effect on the flow of the UHPC. That is, the flow was observed to decrease as the ambient and internal temperatures increased, whereas there is no clear trend in compressive strength with varying ambient or internal temperatures.

Table 3: Compressive strength and flow results from first bridge

Time Sampled	Date	Application	Spread (in)	Ambient Temp. (°F)	28-day Strength (ksi)
8:45 AM	8/24/21	Pile cap	11	49	18.4
10:50 AM	8/24/21	Pile cap	11	61	18.8
1:05 PM	8/24/21	Pile cap	10.25	72	16.6
1:45 PM	8/25/21	Keyway	10.5	74	18
2:35 PM	8/25/21	Keyway	10	82	18.2
3:20 PM	8/25/21	Keyway	10	88	15.7

Table 4: Compressive strength and flow results for second bridge

Time Sampled	Date	Application	Spread (in)	Ambient Temp. (°F)	Internal Temp. (°F)	28-day Strength (ksi)
7:50 AM	9/14/21	Pile cap	11	42	61.6	18.5
10:00 AM	9/14/21	Pile cap	10.5	55	67.9	17.7
11:15 PM	9/14/21	Pile cap	10	62	71.9	16.7
1:45 PM	9/15/21	Keyway	8.75	82	78.4	17.6
3:00 PM	9/15/21	Keyway	9.5	84	75.4	16.5
3:50 PM	9/15/21	Keyway	9.5	84	76	17.8

6.7 Costs

The costs of using MT-UHPC in this project as estimated by the contractor are presented in Table 5. These costs were estimated by the contractor after the completion of the project. As can be observed in this table, the cost of the constituent materials was \$1550/yd³, with the most expensive component being the steel fibers, which accounted for approximately half the total cost. These material costs include the freight from the source to the contractor's yard in Helena. The premixing and bagging of the dry mix cost \$850/yd³. This brings the total cost for the materials to \$2400/yd³, including pre-bagging. The grinding of the UHPC after placement was estimated at \$370/yd³, while the placement was estimated at \$1,790/yd³, bringing the total cost of using MT-UHPC on this project to \$4560/yd³.

Table 5: Cost of MT-UHPC per cubic yard

Item	Cost/cy
Cement	\$ 237
Silica Fume	\$ 174
High Range	\$ 204
Fly Ash	\$ 68
Steel Fibers	\$ 790
Sand	\$ 77
Materials Subtotal	\$ 1,550
Mixing/Packaging	\$ 850
Total Material Cost	\$ 2,400
Grinding	\$ 370
Placement	\$ 1,790
Total	\$ 4,560

7 Summary and Key Findings

The nonproprietary UHPC developed by MSU (MT-UHPC) was successfully used in two ABC bridges on Highway 43 around 17 miles west of Wisdom, MT. The MT-UHPC was used in the field-cast joints connecting the precast concrete bridge elements. Specifically, MT-UHPC was used in the: (1) connection between the piles and pile caps, (2) connection between the precast/prestressed longitudinal beam elements and the pile caps, (3) keyways between the beam elements, and (4) connections between the wing walls and pile caps. Based on this experience, the following conclusions can be made.

- Pre-mixing and bagging the dry constituent materials (i.e., cement, fly ash, silica fume, and sand) was an effective/efficient strategy for the implementation of MT-UHPC in the field.
- The on-site batching and mixing methods worked well. However, the use of larger mixers should be investigated. The 3-ft³ limit per batch resulted in an excessive number of mixes per application, which slowed progress on the bridge.

- The MT-UHPC was successfully mixed, batched, placed, and cured under varied environmental conditions. Specifically, temperatures ranged from the low 20s to the upper 80s (°F), and moderate winds were present. That being said, these varied environmental conditions did affect the behavior/performance of the UHPC. Specifically, low temperatures were observed to cause issues with mixing if the mixers were not warmed up prior to batching, and were observed to increase cure times. Whereas, elevated temperatures were observed to cause mixes to setup prematurely in the mixer, and cause mixes to stiffen up quickly during placement. Wind was observed to reduce workability during placement.
- The maturity method provided an efficient and accurate means for estimating the early strength of the MT-UHPC in the field, significantly reducing the number of cylinders required for testing and allowing for a more rapid indication of when the UHPC reaches the required strength for construction loads, which is especially important in accelerated bridge construction projects such as this.
- The top-forming method used on this project could be improved. The method used resulted in several locations with an insufficient depth of UHPC, requiring epoxy coating after grinding.
- The Special Provisions developed for this project were a good starting point for implementing MT-UHPC in a bridge construction project in Montana. However, they should be updated and modified for future projects to incorporate some of the key findings from this inaugural project.
- It was imperative to establish a good working relationship with the contractor and establish good lines of communication. The contractor on this project, Dick Anderson Construction, was a pleasure to work with, making this project possible.

Overall, this project was a successful demonstration of using a nonproprietary UHPC in field-cast joints for an accelerated bridge construction project. All placed UHPC had adequate flows, gained strength quickly, and reached the required minimum compressive strengths.

8 References

1. Berry, M., R. Snidarich, and C. Wood, *Development of Non-Proprietary Ultra-High Performance Concrete*. 2017, Montana Department of Transportation.
2. Berry, M., K. Matteson, and R. Scherr, *Feasibility of Non-proprietary Ultra-High Performance Concrete (UHPC) For Use in Highway Bridges in Montana: Phase II Field Application*. 2020, Montana Department of Transportation.